Gaspard Monge Program for optimization and operational research

2016 Call for projects

Appendix :
IROE Optimisation Problems

Sommaire / Summary

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1 Introduction

This paper aims to describe in details some of the problems of energy management, and to give an idea of the work already completed or in progress on these topics, and the main difficulties already encountered. The listed research directions are given as an example. The submitted projects may address other issues than those listed below or consider methods of resolution that are completely different or that are a continuation of the works quoted.

Proposers are strongly encouraged to contact the experts at EDF R&D on each subject in order to have a thorough knowledge of the issues and research works already done or committed on each topic. For this, thank you to contact the PGMO board (mailto: pgmo@fondation-hadamard.fr).

2 Background: the main issues in Energy Management

2.1. Managing the Supply-Demand balance

In order to generate electricity, a diverse portfolio of physical and financial assets (supply) is available in order to meet the customers consumption (demand). The balance between supply and demand must imperatively be reached at each time period in order to avoid the risks of physical system failures. The objective of Generation Management is to achieve this balance at minimal cost.

2.1.1. Uncertainties

Many uncertainties significantly impact the management of production either from the point of view of system safety than from the economic point of view. These uncertainties are mainly due to climate (temperature - which strongly influences the demand for electricity-, hydraulic inflows, wind, cloud cover, sun), outages of power plants, prices on the energy markets, renewable production (wind and photovoltaic). Those uncertainties are strongly correlated one to each others.

2.1.2. A diversified generation portfolio

The physical offer is the production of the assets portfolio:

- **The thermal park**, consisting of nuclear and conventional thermal power plants: coal, oil, gas turbines, GCCs. Each plant has to respect a set of constraints (production ranges, minimum periods stop or run, start-up curves, possibly common fuel stock to several plants ...) and is characterized by a complex cost structure (fixed costs or depending on the amount of fuel, startup costs ...);
- **The hydraulic park**, consisting of hydraulic plants located in valleys with water route between plants whose duration vary depending where the plants are located, constraints on reservoirs (minimum and maximum volumes, water values…) and plants (power limitations, discrete operating points, gradient constraints, change of direction constraints ...).

2.1.3. Contracts

- "Tariff options" or Demand Side Management ("effacements" in French) , ie. the ability to induce a customer not to (or less to) consume during a given period of time in exchange for a special rate outside this period;
- Swap contracts with other producers;
- Electricity and commodities markets (spot and futures markets where many products are available, options markets ...)

2.1.4. Environmental constraints

The directives and guidelines initiated by the European Union in order to foster a general approach against climate change and for environmental protection have a strong impact on the management of the supply- demand balance for energy producers:

- control of greenhouse gas emissions: management of pollutant emission;
- taking the increase of the renewable generation (wind, photovoltaic ...) into account, inducing high uncertainties.

2.2. The challenges : Manage a diversified portfolio of very large size

The goal is to manage the portfolio (generation assets and contracts) in the objective of minimizing costs while considering uncertainties. This problem is not solvable in the present state of knowledge, because of its very large size and its mathematical complexity. It then has to be decomposed into a set of problems per time horizons on the following principle: at distant time horizons, the most important hazards (weather hazards, hazards on the operation of power plants, market risks ...) are represented very accurately (in practice as random process or a very large number of scenarios), while the generation assets are briefly described, and vice versa, at close time horizons generation assets are described very precisely, but uncertainties are not represented.… Each time horizon provides a set of indicators for the closer time horizons, in order to give a vision of the future and to keep all this coherent.

At each time horizon, optimization problems remain, however, very large, leading to a particular difficulty related to computing time, because the operating process has to comply with strong planning constraints.

2.2.1. Long-Term

In the long term (five to twenty years), the questions are:

- simulate the evolution of prices of fuels and electricity, which are based on the calculation of underlying fundamentals, ie, a model of the supply-demand balance over a set of interconnected geographical areas;
- plan investments in new generation assets. Investment planning methods are based on a minimization of the supply-demand balance cost, the result being the optimal (and robust to uncertainties like physical hazards, economic and regulatory uncertainties) distribution of technologies to meet base and peak demand.

More details may be found in [LAB2011].

2.2.2. Mid-Term

In the mid-term (one to five years), the questions are:

- **Defining the optimal outage schedules for refueling the nuclear reactors**, in order to minimize generation costs while satisfying a number of constraints on either the generation of each reactor, the dynamic constraints of each reactor and constraints on the dates of the outages (earlier of later dates, minimum/maximum spacing or recoveries between outages ...), this regarding numerous uncertainties. A detailed description can be found on the PGMO web site and in [ROAD2010].
- **Defining coordinated management strategies for a set of stocks** (lakes, fuel stocks, stocks of "effacements", pollutant emission stocks): the aim is to calculate optimal strategies that adapt themselves to uncertainties (feedback, "multi-stage" with recourse, ...). One of the main issues is relative to the joint optimization of all stocks. Currently, difficulties appear beyond three stocks due to the limitations of the techniques used (dynamic programming). In addition, the uncertainties models are not very accurate, which raises many questions of how to describe those hazards in the optimization problem. (see [L2008], [G2010] for more details).

2.2.3. Short-Term

In the short-term (a few days to a few hours), the questions are to define a day-ahead production planning and to adjust near real-time schedules to meet the actual demand. The main issues are:

- Calculate minimum cost generation schedules for the next day, complying all constraints on generation assets, meeting the demand constraint (power and reserves) while providing recourse schedules in order to take into account future uncertainties.
- Optimize Intra-Day rescheduling ("redeclarations" in French): at each hour of the day, the producer must change the schedules of a limited number of assets (thermal assets or parts of hydro-valleys) in order to reduce the real-time production-consumption gaps due to uncertainties on demand and availability of assets.
- Calculate generation margins and optimize reserves.
- Calculate balancing offers for the adjustment market.

More details are available in [HBML2010]. A very detailed description of the problem, as well as presentations explaining the state of the art on this issue are available on the PGMO web site.

3 Main research topics

The list of all already funded PGMO projects may be found on the PGMO web site.

3.1. Fundamentals and Investments

3.1.1. Fundamentals (long-term)

Fundamentals models are designed to calculate the long-term prices of energies on a set of interconnected areas. In the case of electricity, the main difficulty comes from the representation of the various stock management strategies, water in particular. The mathematical model associated with these issues is a problem of economic stability across Europe, each actor aiming at minimizing its costs while providing energy to its customers. Balance prices calculated with this model will be interpreted as price indicators of electric energy. The main difficulty comes from calculating optimum strategies for the management of interconnected stocks, with a good representation of the uncertainties. A recently proposed method is to solve this problem using a quantities-decomposition algorithm associated with an SDDP algorithm for optimising the reservoirs management strategies [LBD2012].

See also the PGMO project "Proximal decomposition of stochastic programs for long-term multi-zonal generation management".

In summary, the scientific barriers are:

- The stochastic optimal control in a large state space (SDDP, decomposition / stochastic coordination with incomplete information). This scientific barrier is common with the problems of middle-term management of hydraulics.
- The equilibrium calculations with stochastic models (stochastic games ...). This scientific barrier is common with decentralization issues.

3.1.2. Investments

The issue of this problem is to determine the technologies in which it will be best to invest in the future in order to meet energy demand. Due to the nature of those investments (construction of a plant, modification of the network, ...), it is necessary to anticipate them far in advance. In other words it is necessary to take all relevant information necessary into account to determine the right sizing of production facilities on the horizon 15-20 years, such as: changes in the price of fundamentals (fuel prices ..), the evolution of energy demand, or assumptions related to the energy policy in Europe.

We can refer to [G2014] for more details and a description of the work already done on this subject. Formulations of the problem have been proposed and are available. ***This problem is one of the topics of great interest to this call for projects.***

3.2. Scheduling outages for nuclear refueling

Stopping a nuclear reactor can lead to substitute other types of power plants whose production cost is higher. Scheduling the outages of nuclear reactors is then a major optimization problem. Its objective is to determine the outage dates, the quantities of fuel to refill and a production planning (meeting demand at minimum cost) for all plants. The outage dates must satisfy many constraints: bounds on the amount of remaining fuel at the time of the stop, minimum or maximum time spacing between stops, resource constraints limiting the number of stops running in parallel ...

Given that this optimization is done on a multi-year planning horizon, most of the data is not known at the time of optimization. This is the case of the demand to meet at any time, the availability of production units, the duration of maintenance operations during reactor outages, prices and exchange capacities on the electricity markets. The provisional schedule is calculated over five years, and is re-optimized every month to take care of the uncertainties that happened over time, and of the updating of forecasts.

This very large stochastic combinatorial optimization problem was proposed as the topic of the EURO/ROADEF challenge in 2010 [ROAD2010], in a simplified form. In particular, the uncertainties on the length of nuclear reactors outages and on the availability of production units were not taken into account, as well as the "multi-step" aspect of the operational process (consisting in changing the schedule of some outages each month and keeping some others permanently when coming closer to real time). The solutions offered by the top teams, mostly based on "Local Search" approaches (gradual improvement of the solution through neighborhood searches) are able to provide good solutions quite quickly, but cannot guarantee optimality and do not take any robustness criteria into account.

That is why some work was initiated, aiming to investigate exact resolution methods, capable of taking into account the missing aspects of the EURO / ROADEF Challenge.

These works can be classified into two broad categories:

- First : prospective research on the potential contributions of Semi-Defined Positive programming, including robust formulations or based on probability constraints in order to take uncertainties into account (see the PhD "positive semi-definite programming: methods and algorithms for energy management", supported by A. Gorge in September 2013 ([Go2013], [GLZ2012a], [GLZ2012b], [GLZ2012c], and the PGMO project launched in 2012 "combinatorial optimization under joint probability constraints: application to the nuclear outages scheduling problem ").
- Second : applied research, aiming at using Dantzig-Wolfe like decomposition techniques (column generation) and Benders like methods (cuts generation) on "extended" reformulations of the complete problem, taking the uncertainties on the outages duration into account and the problem of the stability of the outage schedules calculated in the multi-step decision process. (See [HBDPMSV14], [D2014]. [PWEJPBP 2014]). Two PGMO projects are contributing to this works : « Optimising the nuclear plants outage scheduling : stability of the monthly rescheduling process », « Dantzig-Wolfe and Benders decomposition, application to the scheduling of nuclear plants outages with uncertainties on demand ».

3.3. Centralized vs Decentralized Optimization, local actors

The recent emergence of smart grids together with regulatory and contextual changes in the field of energy markets lead us to think about the impact on the traditional optimization models this may have.

3.3.1. Centralized Optimization

The generation management process at mid-term-term horizons of energy is conventionally done in France in a centralized way. This problem has been studied for many years and various approaches have been proposed around stochastic decomposition methods applied to the mid-term optimization problem of an electricity generating facilities subject to a supply-demand equilibrium coupling constraint within a stochastic framework: approaches based on decomposition methods, stochastic optimal control, dynamic programming... (See [E2008], [L2008], [B2004], [D2006], [CCD2009], [RS2011], [BCG2010], [G2010], [A2013])

3.3.2. Decentralised Optimization

Here, we will focus on the relationships between centralized power system management (supply-demand balance on a global scale and network balance management) and decentralized management (local management, due to the emergence of new players and means of production: photovoltaic, wind, smart grids, storage ...). ***This topic is fairly new and deals with issues at different levels of the supply-demand balance process.***

Looking at a local level, new problems appear, which are related to the emergence of local players. The modeling of these problems, especially in a context of intermittent energy is a topic in itself. Regarding the global supply-demand balance, one can addess two questions : i) what are the role and impact of local actors on the centralized management ? ii) What will be the signals that are transmitted between the different actors and how will we model them?

Supply and demand will have to be optimized jointly by both centralized and local actors (multilevel decisions), which will induce bilevel optimization problems.

The emergence of local actors also suggests to consider problems related to network and joint 'network- generation-demand flexibilities' optimization problems. (considering mainly the distribution network), and problems relative to modelling the behavior of consumers in a competitive context.

Formulations of these new problems are ongoing. Some mathematical approaches were identified including:

- Bilevel optimisation in a multi-leaders- multi followers case
- Quasi-convex optimisation
- Decomposition Methods (PGMO project "Decomposition / Coordination for Smart Grids")
- Game Theory

See also PGMO Project "Centralized versus Decentralized Energy Management in a Stochastic Setting"

3.4. Short-term Generation Scheduling

The "Unit Commitment" problem consists of finding a minimum cost operating program for all power plants:

- providing adequate systems services;
- ensuring the supply-demand balance at every half-hour;
- respecting all operational constraints.

3.4.1. Daily and Weekly Optimization

The objective is to determine the optimal generation schedule which minimizes costs (production costs and start-up costs), while meeting exactly the set of "demands" (consumption, reserve capacity and system services) and complying the numerous operational constraints that affect thermal and hydraulic power plants. Solving this problem will determine the day before a reference schedule for the next day.

This Unit Commitment problem is long known, many research studies have already been made. The current solution is a combination of Lagrangian dualization, price-decomposition and bundle algorithms (see [LS1994]). This gives a first schedule which will then be adapted using an Augmented Lagrangian technique combined with the use of the auxiliary problem principle to get the reference schedule (see [CZ1984], [BR1992], [MS1983], DGL2005]). This solution gives excellent results on the historical deterministic problem.

Recently, the strong increase of "new" renewable energies (wind, solar) forced to rethink the problem. Indeed, if "historical" uncertainties (consumption, water intake, failures) could be neglected on a very short-term horizon, it is no longer the case for these new hazards, due to their high non-predictability characteristic (we have no reliable forecasts beyond a few hours) and their intermittent nature (eg clouds passing moves the photovoltaic generation abruptly to 0). It is essential to address these new phenomena.

- First, to model finely all operational constraints in order to benefit from the flexibility of all production facilities, particularly in hydraulics, leading the introduction in particular of the many non -convex or binary constraints. That detailed modeling of the constraints induces difficulties on the overall resolution of the problem because the sub-problems coming from the prices decomposition become more difficult to solve, so are solved in an approximate way which is not compatible with the traditional algorithm. To solve this problem, a new bundle method capable of dealing inaccurate Oracle was developed. A PGMO project (Consistent Dual Primal Signals and Optimal Solutions) aims to improve the resolution by Lagrangian dualization through incorporating heuristics and improving the bundle algorithm. A new line of highly prospective research concerning the non-convex duality and interpretation of dual variables associated is also identified.
- Second, take the uncertainties into account through the calculation of robust production programs, ie where the cost of adapting to the occurrence of intra-day hazards is minimal, so this problem can be formalized as a problem with recourse. Work has been done on a robust approach without recourse decisions, as well as a robust approach with recourse decision but on small convex problems (cf. [BS2011] [Ap2007] [AHMZ2011]). More recently, advances were made through the PhD thesis

[A2013b] and a PGMO project (optimization under uncertainty for the problems of "Unit Commitment") looking at the real problem is ongoing. An approach based on stochastic optimization using uncertainties trees is also addressed in a PGMO project (A Stochastic Programming Approach to Finding Robust Reference Schedules for the Unit Commitment problem).

3.4.2. Intra-Day Optimization and Re-Scheduling

Regulatory developments have led to formulate a new problem on the Infra-Daily horizon : recalculating production schedules by solving the same problem as above plus a so-called re-scheduling constraint which specifies the maximum number of plants (about 30 out of 150) for which the reference schedule can be changed. This constraint is both coupling and combinatorial. Heuristic methods were considered: the problem is decomposed into a phase of selection of plants in which the schedule will be changed then a phase of optimization of the schedules of these plants.

Work is currently being undertaken around a method consisting in using a supervised learning algorithm to decide the list of plants whose program will be moved and a classic Unit-Commitment problem.

Some "Group Sparsity" approaches are also under investigation (see [ABLEGRZ2014], and the PGMO project "Robust Sketching for Structured Multi-Instance Optimization with Uncertainty, Application to Energy Management").

Recent regulatory evolutions may make it necessary to reduce the time steps of the models. Typical timestep in daily/intraday process is 30 minutes which may go down to 15 or even 5 minutes. An answer to these changes may be to have a time continuous model, which may lead to developing completely different optimization methodologies.

In summary, the scientific barriers identified on the daily / intraday are:

- Decomposition methods for dual approaches best suited to non-convexities
- The existence and calculation of marginal indicators which can be economically interpreted
- The formalization / resolution of unit-commitment in an uncertain environment with recourse decisions
- ***Developping new approaches for solving the problem on a continuous-time horizon***

3.4.3. Margins and Reserves Optimization

The objective is to jointly optimize production programs and reserves, taking into account all the hazards.

3.5. Optimization of hydro-electric valleys

At long and mid-term, the objective is to calculate good management strategies for the valleys, taking some constraints on the reservoir levels into account. In the short term the problem amounts to computing feasible programs (ie satisfying the constraints) in order to allow the use of all flexibilities of the hydraulic park.

3.5.1. Long and medium term

The main difficulty is to calculate the management strategies for coordinated reservoirs while dealing with uncertainties. Some solutions to the classical problem where the reservoirs have to respect a coupling de mand constraint already exist. For more complex structures, for instance 'Cascade' eg when it comes to coordinating all the reservoirs of one hydraulic

Valley, effective methods are still being defined (see [E2008], [L2008], [B2004], [D2006], [CCD2009], [PDG2011], [VP2011], [RS2011]). The stochastic decomposition method developed in the context of the global supply-demand balance [G2010] has been extended to the case of cascade reservoirs by [A2013].

A formulation with probability constraints (for taking into account the volume probability constraints on reservoirs) was proposed. The resolution method is based on the dualisation of the probabilistic constraint ([A2013]).

In summary, the scientific barriers identified in this topic are:

- The stochastic optimal control in a large state space (SDDP, decomposition / stochastic coordination with incomplete information). This scientific barrier is common with the problems of long-term management.

3.5.2. Short-term

The main difficulty is to solve accurately and in a very short calculation time a large mixed integer problem, characterized by very strong constraints.

A thesis and a PGMO project (Optimality for Tough Combinatorial Problems Valley Hydro) are working on to solve this problem by combining mathematical methods and combinatorial optimization heuristics.

Local approaches are also investigated (see PGMO project "Hybrid approaches for solving bi-objective energy problems with low-carbon constraints").

The need to take into account the short-term uncertainties also encourages to solve the problem with taking the hazards into account. A PGMO Project ("Hydro-electric scheduling under uncertainty") aims to combine methods from stochastic optimization and combinatorial optimization.

In summary, the locks on these topics are identified:

- The resolution of mixed variables flow problems very large (hundreds of thousands of variables) this may lead to developing new MILP algorithms which could exploit more deeply the specificities of energy problems using specific symmetries, cuts, decompositions….

3.6. Logistics

3.6.1. Routing Problems

The scheduling and routing problem for technician interventions on the electricity distribution networks is difficult and of high interest due to the number of kilometers and mobilized resources (manpower, vehicles and equipment).

This problem can be decomposed in several coordinated stages :

- Strategic : deciding where to settle all sites (ie the premises where the technicians and their vehicles are based), taking into account all different activities organized there, and the site capacity (number of employees, number of vehicles), as well as needs and constraints. When the workload changes, decision makers can explore the interest of reducing or increasing the number of sites and their location, looking at several criteria;
- Operational : determining the daily routing of all technicians of a given site, while meeting the demand (list of operation applications, e.g. maintenance of an electric line…) and taking into account several criteria (distances, equipments that have to be loaded in each vehicles at the beginning of the day, necessary qualifications to perform the operations, ...).
- Real-Time : adjusting the routing schedule to the occurrence of unforeseen events (cancellation, weather ...).

This problem can be seen as a multiple Vehicle Routing Problem with Time Windows. Current work was conducted on a simplified problem (operational stage only), using local search techniques and mixed integer linear programming.

Further researches could focus on the following difficulties :

- Integrating all accurate constraints of operational planning within a strategic planning model, while modeling the evolution of the load.
- Looking at future business needs: touring can be single or multiple ie. taking into account vehicles with only one technician or several technicians. Multi-modal touring : conventional vehicle, electric vehicle, bicycle and / or walking.
- Multi-site problem : technicians of a given site may take in charge operations that are at the border of neighbourhood sites.
- Robust approaches or online optimization for operational planning
- Dynamic readjustment of the touring schedule. This problem is of high interest for PGMO.

3.6.2. *Optimizing maintenance programs:*

The idea is here to find the schedule that will optimize the Net Present Value of the maintenance program (the NPV is the economic indicator balancing investments cost and benefits created by these investments) while fulfilling various constraints (precedence between investments, limited number of investments, budget limit…).

- What we have: we developed a tool, that use Genetic Algorithm to make this optimization based on an evaluation function that gives expected values through Markov graphs.
- What we would like to have: we would like to be able to make the same optimization based on risk indicators and not only expected values. We have the model to assess these risk indicators based on Monte-Carlo simulation but calculations are too long for usual optimization methods .

The two research areas would then be to works on:

- Simulation-Optimization
- Robust Optimization

3.6.3. Optimizing spare parts stock:

The idea is here to find the number of spare parts that will minimize the global owning cost (sum of purchases and shortage costs).

- What we have: a tool that calculates the global owning cost with a closed-form expression. The "optimization" is made with a greedy algorithm iteratively buying the spare part with the best improvement over cost ratio until budget limit is reached.
- What we would like to have: we would like an optimization algorithm that gives better results than the greedy algorithm and which would be able to deal with budget uncertainty

The two research areas would then be to works on:

- Simulation-Optimization
- Robust Optimization

3.7. Big size

A general characteristic of all the above problems is their big size, associated to operational needs of fast solving.

All methods meant to accelerate the solving of those problems are of interest.

Some ongoing ideas are to try to exploit the fact that the operational process leads to solving a very high number of very close instances.

Online optimization, sketching methods and learning are investigated through PGMO projects "Robust Sketching for Structured Multi-Instance Optimization with Uncertainty, Application to Energy Management', 'Reducing combinatorial by using learning methods'

Alternative methodologies would be appreciated.

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